The StarLight Interferometer Architecture and Operational Concepts

Riley Duren*, Oliver Lay, and Matt Wette
Jet Propulsion Laboratory, California Institute of Technology

ABSTRACT

The StarLight flight project was designed to demonstrate the key technologies of spaceborne long-baseline stellar interferometry and precision formation flying for potential use on the Terrestrial Planet Finder (TPF) and other future astrophysics missions. Interferometer performance validation could be achieved over a 6-12 month period by obtaining several hundred fringe visibility amplitude measurements for stars in the band 600-1000 nm for a variety of stellar visibilities (0.2-1.0), magnitudes (Mv = 2-5), and baselines (B = 30-125 meters). Interferometry could be performed both in a 1 meter fixed-baseline combiner-only mode and in a two-spacecraft formation mode. In formation mode, the combiner spacecraft would remain at the focus of a virtual parabola, while the collector spacecraft assumed various positions along the parabola such that the two arms of the interferometer remained equal over a variety of separations and bearing angles. Challenges to be encountered in flight include high-bandwidth inter-spacecraft stellar and metrology pointing control, alignment and shear correction, delay and delay-rate estimation, visibility calibration, and robust fringe tracking in the presence of local and inter-spacecraft dynamics. This paper is based on the StarLight project design-capture of March 2002 and will describe the StarLight Interferometer System architecture and selected operational concepts (both of which have relevance to the on-going TPF Technology Program).

Keywords: stellar interferometry, formation-flying, planet detection, Terrestrial Planet Finder

1. INTRODUCTION

One of the leading architecture options for the Terrestrial Planet Finder (TPF) is a five-element, formation-flying nulling interferometer[1]. However, while formation-flying interferometers have many advantages over monolithic instruments, they require new, largely unproven technologies associated with providing precise and reliable stellar beam transport between multiple free-flying spacecraft and maintaining the necessary knowledge of the formation geometry to enable the fundamental measurement[2]. This results in a highly complex, multi-tiered system for providing the knowledge and control necessary to operate such an instrument.

The StarLight mission, part of JPL's Navigator Program, was originally scheduled for a 2006 launch into an earth-trailing heliocentric (SIRTF-type) orbit. StarLight was intended to validate the technologies of spaceborne long-baseline optical interferometry and precision formation flying for potential use on the Terrestrial Planet Finder (TPF) and other future astrophysics missions. The flight development activities of StarLight were terminated in March 2002 (late in the project Mission and System Definition Phase). Since then, the StarLight project has been merged with the Terrestrial Planet Finder Project and will continue to develop ground technologies for formation-flying interferometry, with a goal of supporting the final TPF architecture selection in 2006[3]. For the remainder of this paper, we will describe the StarLight Interferometer as the point design developed at the time of termination of the flight portion (including the use of the future tense).

Interferometry on StarLight will be performed both in a 1 meter fixed-baseline combiner-only mode and in a formation-flying mode, in which two spacecraft operate in a novel Parabolic Geometry Interferometer (PGI) configuration[4]. The StarLight interferometer will obtain >100 fringe visibility amplitude measurements for stars in the band 600-1000 nm with a variety of stellar visibilities (0.2-1.0), stellar magnitudes (Mv = 2-5), and baselines (B = 30-125 meters), equivalent to spacecraft separations of S =40-600 meters. These measurements will provide a characterization of the formation-flying interferometer performance and demonstrate the robustness of this technique for TPF. A more comprehensive overview of the StarLight Project is provided in a companion paper by Blackwood, etal[3].

* riley.m.duren@jpl.nasa.gov, (818) 354 – 5753, 4800 Oak Grove Drive, M/S: 264-459, Pasadena, CA, USA 91109

2. INTERFEROMETER SYSTEM OVERVIEW

This paper represents a snapshot of the Interferometer System design as it existed in March 2002, approximately 2 months before Interferometer PDR. The StarLight Interferometer is essentially a conventional Michelson stellar interferometer design adapted to a space-based, formation-flying platform. The Interferometer System includes the following subsystems, each of which will have components on both the combiner and collector spacecraft: Stellar, Metrology, Optical Bench, Electronics, and Flight Software. Additional information on the individual Interferometer subsystem designs is provided by Duren and Lay[5] and a detailed description of the optical design and performance analysis is provided in another companion paper in this conference by Martin, etal[6].

2.1. Some Driving Requirements

A list of some challenging requirements driving the interferometer system design is presented in Table 1. The ultimate validation of the StarLight Formation-Flying and Interferometry technologies will be the characterization of system performance by obtaining a set of fringe visibility amplitude measurements on a variety of stars spanning a range of baselines (the project requirements described briefly in Section 1). The resulting instrument visibility and limiting magnitude requirements are based on target star analyses in which a reasonable number of stars (~20), spanning the visibility space from unresolved (1.0) to well-resolved (0.2), were identified as suitable for observation by StarLight. In order to minimize thermal distortions, the StarLight Interferometer will be continuously shielded from the sun during the 6 month operational phase of the mission. This places some constraints on the availability of stars for repeat observations (i.e., stars within 26 degrees of the celestial poles are continuously observable, with availability dropping to about 30% of the time for stars near the ecliptic). Also, targets must meet strict criteria to be suitable in terms of visibility (i.e., binaries and stars with large apparent diameters are excluded).

The stellar pointing control requirements are driven by the visibility requirement (i.e., the precision required to control the fringe spot overlap for both arms of the interferometer). Pointing control is also obviously important for star acquisition although the precision is somewhat looser than that driven by visibility. A note about control bandwidths: the original design assumed we need a 50 Hz closed-loop bandwidth for the stellar pointing control loops. Recent analysis suggests that we may only need 15-20 Hz bandwidth. In any event, sensor latencies associated with the stellar pointing servo drives a challenging 500 Hz sample rate requirement for the camera. This is consistent with the need to provide 500 Hz camera sampling for actual fringe tracking.

Requirement	**Spec**
Instrument Visibility (white-light)	0.47
Visibility Stability	0.02
Limiting Magnitude (Mv)	5.0
Stellar pointing, each arm -control (per axis, 1 sigma, on-sky) -knowledge (per axis, 1 sigma, on-sky) -closed-loop bandwidth:	 0.25 asec 0.20 asec 20 Hz
Interspacecraft (Metrology) pointing -control (per axis, 1 sigma) -knowledge (per axis, 1 sigma) -closed-loop bandwidth:	 25 mas 18 mas 20 Hz
Optical pathlength control, left arm -control (RMS) -knowledge (RMS) -closed-loop bandwidth:	 35 nm 11 nm 300 Hz
Delay-rate estimation (initial knowledge)	20 µm/s
Stellar Line of Sight knowledge	10 asec
Stellar/Metrology co-alignment, on sky	1.4 asec
Passband (pointing) (fringes)	400-600nm, 600-1000nm
On-orbit lifetime (design for)	12 months

Table 1 Some driving requirements

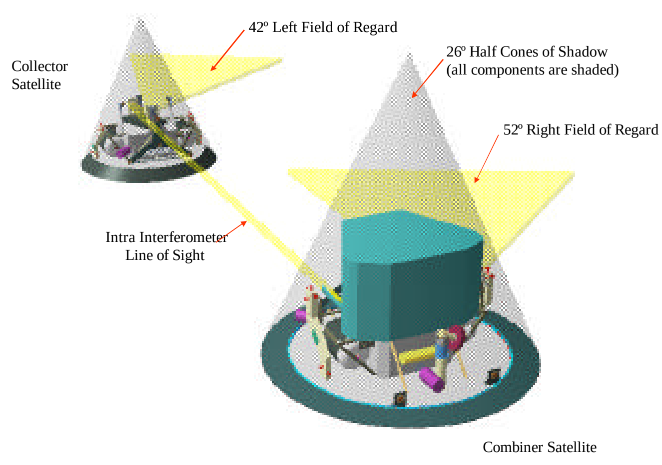

Figure 1 - Formation Configuration

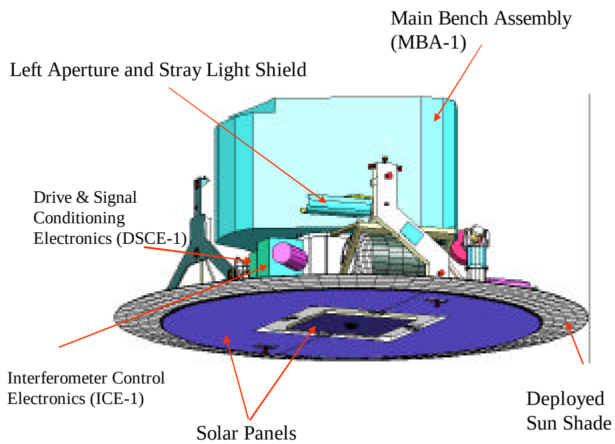

Figure 2 - Combiner Satellite

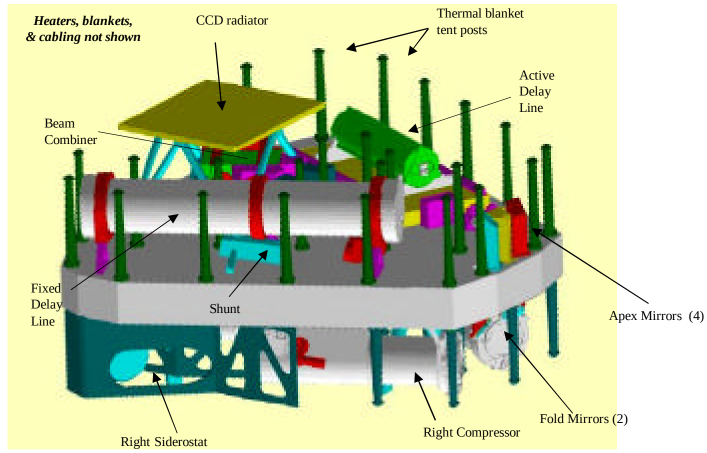

Figure 3 - Combiner Main Bench

The interspacecraft pointing control accuracy is likewise driven by the instrument visibility requirement. Whereas the stellar pointing control requirement refers to inertial pointing on each spacecraft, the interspacecraft pointing requirement refers to the need to compensate for relative motion between the two spacecraft.

The optical pathlength control requirement refers to the need to adjust the left arm of the interferometer in order to compensate both for local pathlength changes (combiner-only) as well as delay residuals between spacecraft. Again, this is driven by the visibility requirement. This control requirement drives the Metrology Subsystem to provide optical pathlength knowledge for both arms of the interferometer to an accuracy of 11 nm, 1 sigma at a sample rate of 3 KHz.

Interferometric fringe detection on StarLight is challenging due to delay and delay rate uncertainties. Delay uncertainty means the exact optical path delay for each observation varies due to the fact that formation-flying isn't perfect (i.e., interspacecraft range uncertainties exist). It follows that the optical path delay is also likely to be time-varying due to spacecraft formation (range) control residuals so even if one knows where to look for the fringe, it's easy to lose unless one knows which way it's moving. Therefore, on StarLight, fringe acquisition is preceded by an iterative process known as delay and delay-rate estimation and formation trimming. This process has been described in detail by Lay, etal[2,7] but it's worth mentioning that the delay rate estimation in particular poses challenges for the interferometer system (e.g., left stellar angle rate knowledge of 14 mas/s).

2.2. A Tour of the Interferometer

As shown in Figure 1, there are two "arms" of the interferometer, defined from the point of view of the interferometer camera located at the beam-combiner focal plane on the combiner spacecraft (more on this to follow). The right arm extends towards to the star. The left arm extends towards the star via the collector spacecraft, whose primary purpose is to host a relay mirror. The large Fields of Regard in azimuth are to accommodate the wide range of formation geometries required for multiple baselines.

2.2.1 Combiner Hardware

Figure 2 depicts the combiner spacecraft. The disk shaped sunshade/solar array and square structure are referred to as the spacecraft bus. Two of the interferometer electronic assemblies are mounted to the side of the bus: the Interferometer Control Electronics (ICE-1) and Drive and Signal Conditioning Electronics (DSCE-1). The ICE-1 contains a computer which will host the interferometer flight software and also provide data handling interfaces with the spacecraft computer and an interspacecraft communications link with the interferometer hardware on the collector. The large wedge shaped object on top of the bus is the Interferometer Main Bench Assembly. In this drawing, the Main

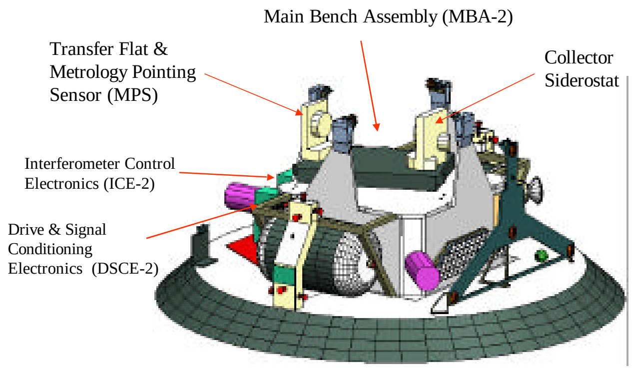

Figure 4 - Collector Satellite

Bench is enclosed by a tent of thermal blankets. Figure 3 provides a side view of the combiner Main Bench (blankets have been removed for clarity). The multiple "tent posts" are thermal-blanket supports. The bench supports all of the opto-mechanical hardware for the Stellar and Metrology subsystems, an overview of which is provided in the upcoming walkthrough of the right and left arms of the interferometer.

2.2.2. Collector Hardware

Figure 4 depicts the collector spacecraft. The collector is a less complex version of the combiner. It hosts a smaller set of interferometer electronics (ICE-2 and DSCE-2) and the collector Main Bench Assembly. The collector Stellar and Metrology hardware is limited to a single siderostat with an embedded retro-reflector and a fixed transfer flat with an embedded Metrology Pointing Sensor (MPS) ,which is a four-element Intensity Gradient Detector. Unlike the combiner bench, the collector bench is not surrounded by a thermal blanket tent (rather, the blankets directly cover the bench).

2.2.3. The Right Arm (refer to figure 5)

Starting with the right arm of the interferometer on the underside of the combiner main bench, incoming light from the star is collected by the right combiner Siderostat, which provides high-bandwidth tip/tilt pointing control and a 12 cm aperture. The starlight passes through a Beam Compressor, which provides 4:1 reduction in beam diameter - allowing smaller downstream optics and stray light reduction - via a pinhole/field-stop. The 3 cm starlight beam is then transferred to the top of the main bench through a periscope arrangement of fold mirrors. The top fold mirror in the periscope (referred to as Right Apex Mirror 1) also provides in-flight precision tip/tilt adjustment to remove quasi-static misalignments and shear of the stellar boresight/line-of-sight. In formation-mode, the stellar beam then enters the Fixed Delay Line (FDL) which contains the 14 meters of optical path necessary to support the combiner spacecraft's position at the focus of the parabola. Alternatively, in combiner-only mode, the FDL is bypassed by a shunt mirror mechanism which deflects the beam into a short cats-eye, thus supporting the 1 meter baseline in combiner-only mode. After leaving the FDL (or shunt), the stellar beam is routed by Right Apex Mirror 2 (also actuated for alignment control) to the Beam Combiner Assembly. The Beam Combiner employs a dichroic beam-splitter and supporting optics to spectrally separate the incoming stellar signals into a set of pointing (400-600 nm) and fringe (600-1000 nm) beams. The four quadrant camera focal plane is thus presented with the following signals. Quadrant 1: left pointing spot (~ 4 pixels). Quadrant 2: right pointing spot (~4 pixels). Quadrant 3: white-light fringe spot (1 pixel, consisting of the overlapped left & right fringe spots). Quadrant 4: four-five dispersed fringe spots (4-5 spots, each 1 pixel across & consisting of the overlapped left & right disperse fringe spots). The dispersed spots refer to a 4-5 channel spectrometer capability used to augment fringe tracking and measurement. A custom camera based on an 80x80 pixel CCD is used as the primary detector for the interferometer. The camera requirements necessary to meet visibility performance are considered challenging, particularly the combination of low read-noise (< 15 e-) and high frame-rates (500 Hz).

While the above description concentrated on the incoming stellar beam, linear metrology of both arms of the interferometer is also critical. For the right arm, the 1.3 µm metrology laser beam is injected via a Beam Launcher on the Beam Combiner sub-bench. The metrology beam is injected at the center of the stellar beam and occupies the inner

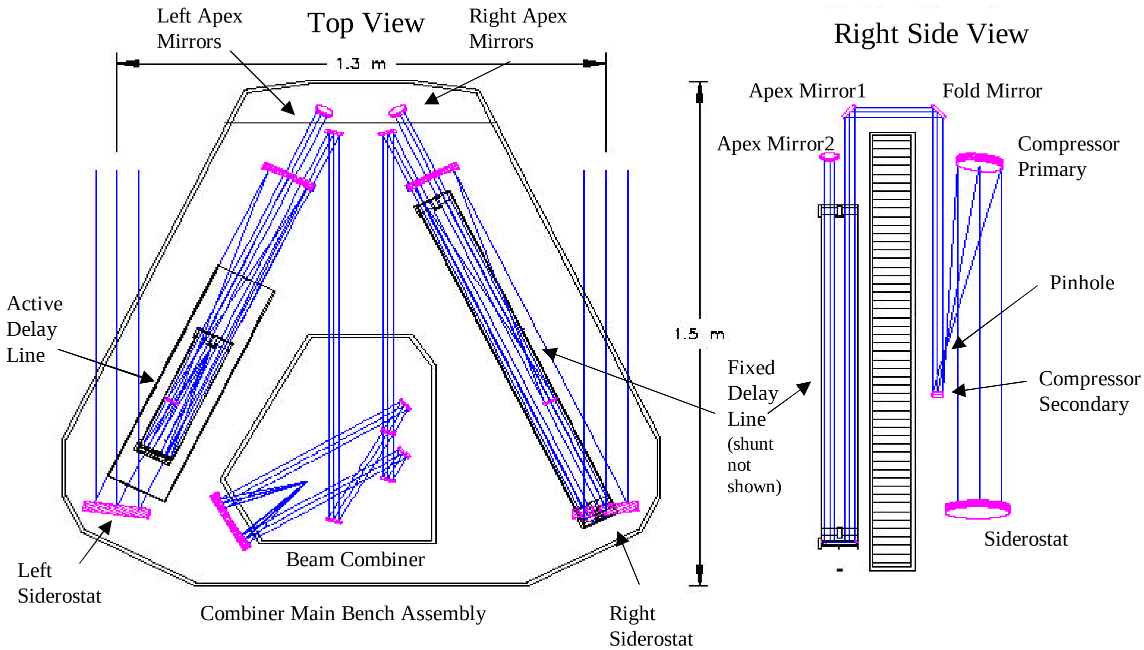

Figure 5 - Combiner Stellar Optical Layout

20 mm of the expanded beam (this fraction of the beam is thus not available for stellar photons). The Metrology beam is directed out of the right Beam Launcher (Figure 6) towards the sky where it encounters retro-reflector C mounted on a spider at the outer aperture of the right Beam Compressor, then returns to the Beam Launcher where it continues to Retro-reflector E mounted on a spider near the main beam splitter, before returning to the Beam Launcher for detection. Note, the error contributed by the unsensed pathlength between Retro-reflector C and the right siderostat is negligible compared to other terms in the budget.

2.2.4. The Left Arm (refer to Figures 1, 5, & 6)

The left arm of the interferometer is similar to the right but with additional complexity. The collector siderostat serves the same purpose as the right combiner siderostat (i.e., points at the star). The stellar beam is relayed to the combiner via a Transfer Flat mirror. Pointing control of Stellar and Metrology beams between the two spacecraft is provided by a combination of Angular Metrology and the Left Combiner Siderostat. Light from the metrology laser (the same source used for linear metrology on the right arm), is injected from a Beam Launcher on the left arm of the Beam Combiner. In addition to the intra-combiner linear metrology, the left metrology beam also monitors the inter-spacecraft path-length and is also used as component of the left pointing control loop (angular metrology). An angular metrology acquisition sequence uses the left combiner siderostat to center the metrology beam on the collector transfer flat via feedback from the Metrology Pointing Sensor (the data is transferred from collector to combiner over the inter-spacecraft comm link). This allows the left combiner siderostat to track relative motion between the two spacecraft. The left metrology beam also continues past the collector transfer flat to Retro-reflector A on the collector siderostat to support the inter-spacecraft linear metrology. Using a single laser beam to sense both the internal and external paths results in some challenges known as the “dual target problem”. Part of this problem is solved by employing a beam-splitter within the spider that holds Retro-reflector B in the entrance of the left Beam Compressor. Thus, part of the laser beam is returned to the Beam Combiner and the rest continues on to the collector spacecraft via the left combiner siderostat. Discrimination between the external and internal targets (retros A & B) is accomplished via phase modulation techniques[8]. Alignment of the left stellar and metrology beams is critical (1.4 arcsec level). Therefore, the left metrology Beam Launcher is mounted to the Beam Combiner via a tip/tilt actuator to allow alignment adjustment.

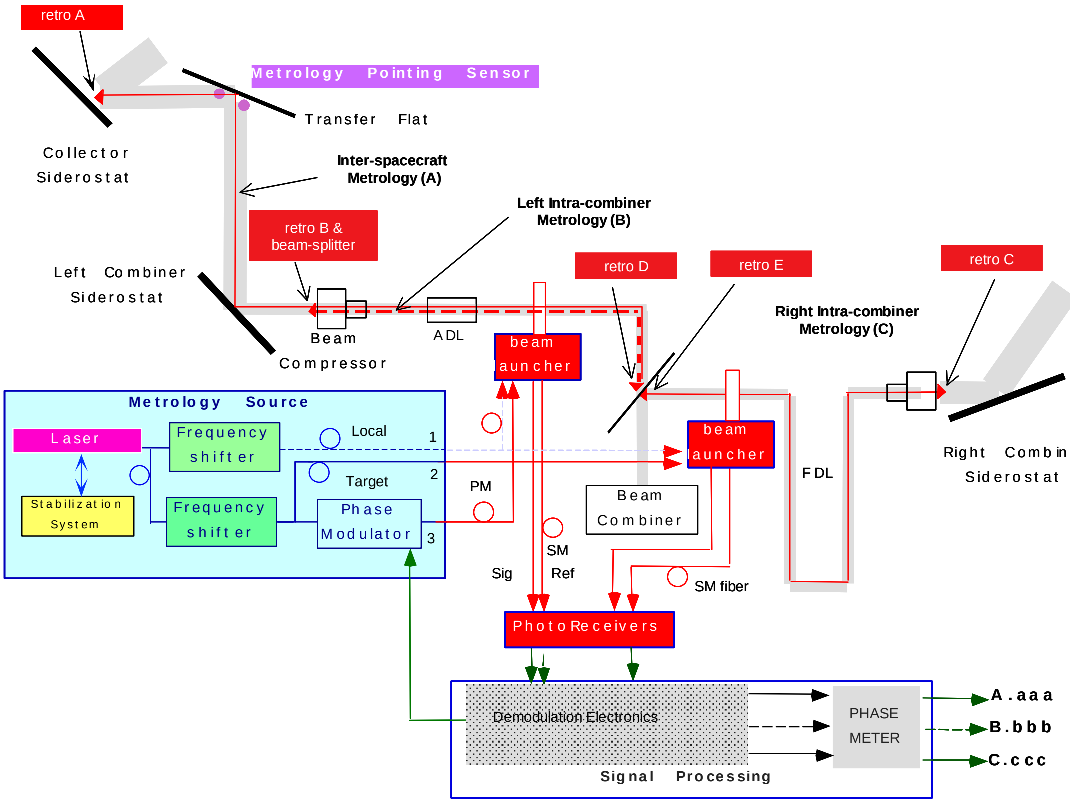

Figure 6 – Metrology Architecture

The only other difference on the left arm is the delay-line. Unlike the FDL and shunt on the right arm, an Active Delay Line (ADL) is included in the left arm to provide the precision path-length control needed for fringe detection. Our ADL relies heavily on inheritance from past delay-line work as part of JPL's Interferometry Technology Program[9,10].

In addition to the hardware already described for support of the primary interferometer function (observing stars), an Internal Test Source (ITS) is provided. It consists of a miniature incandescent lamp, pinhole, and collimating optics for injecting a white-light signal into the system via the partially transmissive fold mirrors on the underside of the main bench. When operating in this mode, the combiner siderostats are placed in the "narcissus configuration" which reflects the ITS photons back into the optical train, where they can be used to characterize combiner-mode interferometer throughput, visibility, and alignment both during pre-flight testing as well as in-flight.

2.3. Thermal and Structural Support

The Optical Bench Subsystem on both the Combiner and Collector is responsible for supporting the components of the Stellar and Metrology Subsystems. Minimizing misalignments is a critical and challenging requirement (i.e., few arcsecond scale changes are allowed). Each bench is constructed of low CTE graphite cyanate-ester composite structures. The Optical Bench Subsystem also provides the thermal control system for the interferometer. Among the key requirements in this area is a need to actively maintain both the temperatures of the combiner and collector main benches to 20 ± 1 degC during observations. This is accomplished via an array of strip heaters covering the bench surfaces and spot heaters on certain opto-mechanical components such as the Beam Compressors. Also, the camera CCD is kept cool (-60 degC) using a radiator to reduce dark current. De-contamination heaters are also provided for sensitive optical surfaces and the CCD. Survival heater control of the optical benches and operational/survival thermal control of the interferometer electronics is provided by the spacecraft bus.

2.4. Electronics

Electrical support for this assortment of opto-mechanical hardware is provided by the Electronics Subsystem, which includes a total of four assemblies, two each on the Combiner and Collector spacecraft bus. The Electronics subsystem will provide power, control, and signal conditioning and processing for the Stellar, Metrology, and Optical Bench components; support a high speed (< 1 msec latency) interspacecraft communication function to close the left pointing control loop; and also host the Flight Software in a dedicated interferometer computer (one each on the combiner and collector). The Combiner and Collector Electronics each include one GD603r computer.

2.5. Algorithms and Software

Flight Software will execute command and data handling, fault protection, and interferometer control algorithms. The control algorithm architecture is shown in figure 7. A description of the key algorithms is provided here as background for the operations concepts discussion to follow.

2.5.1. Interferometer Mode Commander

This module provides overall sequencing and mode-transition control for the various algorithms.

2.5.2. Image Analysis/Processing

The camera plays two distinct roles on StarLight. First, it serves as a "star tracker" (the camera head and electronics and the software together work to support the left and right stellar pointing control loops). This software module reads the full-frame and/or sub-windowed raw camera data and generates centroids for the left and right pointing spots. Second, the camera provides intensity measurements of the White-Light and Dispersed fringe spots. Those intensity measurements constitute the ultimate observable for the interferometer. In addition to being used in real-time for fringe tracking, the raw data will also be recorded and converted to visibility measurements a posteriori (on the ground).

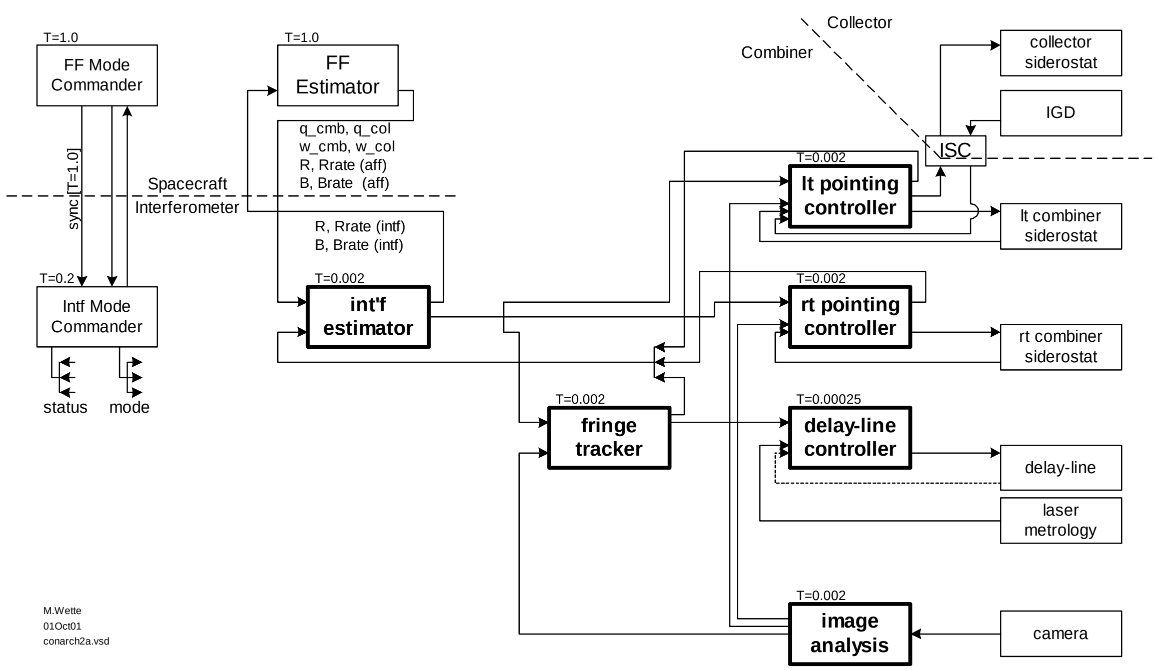

Figure 7 – Interferometer Control Architecture

2.5.3. Delay Line Controller

The delay-line control servo uses the Active Delay Line to control the optical path delay in the left arm of the interferometer. Initially, feedback is provided strictly by metrology (11 nm knowledge at 3 KHz sample rate). However, during fringe acquisition and tracking, feedback is also provided from the fringe tracker servo, which incorporates white-light and dispersed fringe spot intensity measurements from the camera at a 500 Hz sample rate.

2.5.4. Right Pointing Controller

The right stellar pointing servo is responsible for acquiring and tracking the target star on the right arm to the required accuracy (0.25 arcsec, 1 sigma, on the sky). It receives right pointing spot centroids from the camera imaging analysis module and outputs commands to the right combiner siderostat coarse and fine stages. Control of the siderostat coarse stage (setup for acquisition) requires the right pointing controller to read the coarse stage optical encoders. Control of the siderostat fine stage (star acquisition and tracking) is easier in some ways since the siderostat fine stage control is hard-coded in the electronics board which drives the fine stage (i.e., just send the desired position command and receive residuals – no need to deal with raw fine stage encoder data or maintain a "local" siderostat loop).

Analysis suggests a closed-loop bandwidth of 20 Hz is required for all interferometer pointing loops on StarLight but sensor latencies call for extra margin so the ultimate camera sample rate will still probably be around 500 Hz for pointing control.

2.5.5. Left Pointing Controller

The left pointing control servo actually has two components. The left stellar pointing control loop is closed around the collector siderostat and the left pointing spot centroids. This is handled as described above for the right pointing controller. The other component is the interspacecraft pointing loop (also referred to as the metrology pointing loop). This uses the Metrology Pointing Sensor (Intensity Gradient Detector) centroids for feedback and the left combiner siderostat for control via the Inter-spacecraft Comm (ISC) link . The left stellar and metrology pointing loop are ultimately integrated by the left pointing controller.

2.5.6. Interferometer Estimator

The Interferometer Estimator uses information from the Formation Flying (FF) Estimator on the spacecraft computer as well as the other interferometer controllers to derive delay and delay rate estimates which are used to guide formation trimming. These estimates are later refined by feedback from the Fringe Tracker, which provides extremely precise validation of the Formation Flying solutions. This estimator also uses spacecraft attitude data from the FF Estimator (based on star-tracker and IMU observables) to assist with stellar pointing acquisition.

2.5.7. Fringe Tracker

The fringe tracker algorithm is responsible for finding and tracking the fringe. Its functions will be described in section 3.4 as part of the operations overview.

2.6. Summary of Interferometer System Capabilities

A list of key interferometer properties is provided in Table 2 below. This, together with Table 1, provides a high-level summary of the StarLight Interferometer capabilities.

Property	Quantity
Aperture size	12 cm diameter
Actuators	24
Control Loops	Six total: three 20 Hz pointing servos, three delay-line servos (1, 60, 300 Hz BW)
Primary sensors	20 (including one CCD camera)
Engineering sensors	191
Internal Test Source	White light fringe and alignment capability
Optical elements	27
Laser Metrology	1.3 µm, multi-pumped
Optical Bench	High-conductivity Composite facesheets w/honeycomb cores
Heaters	38
Electronic Boards	20 (in 4 assemblies)
Processors	One GD603R, 240 MHz (per Combiner and Collector ICE)
Flight S/W	C++, VxWorks, with 22 modules (some inherited)
Interferometer Mass	Combiner: 146 kg, Collector: 36 kg
Interferometer Power	Combiner: 310 W, Collector: 87 W
Field of Regard	Left Arm: 5 x 42 deg , Right Arm: 5 x 52 deg
Field of View	Stellar Pointing: 1 arcmin, Metrology Pointing: 1 deg

Table 2 – Interferometer Properties

3. OPERATIONAL CONCEPTS

3.1 Operational Overview

StarLight is injected into a helio-centric, earth-trailing (SIRTF-type) orbit. The minimum mission duration is 6 months (extendable to 12 months). After a month or so of initial spacecraft separation, checkout, and formation-flying experiments, checkout and calibration of the interferometer is performed, first using the Internal Test Source, then using combiner-only observations, followed by formation-mode interferometer checkout. Once calibration and checkout is complete, the operational phase of the mission is executed, consisting of several months of formation-mode interferometric observations, with a requirement of obtaining fringe measurements for at least 100 UV points and goal of 500. An Interferometer Operations Plan was created to define in detail the sequence of events, processes, and operational functions needed to guide the system design[11]. Due to space limitations, this paper will only touch on some of the key concepts.

Once the spacecraft and formation-flying systems have been checked out, the high-level sequence of events for the interferometer and approximate durations are as follows:

1. Activation/Initialization: 5 minutes (each; repetitive)
2. Delay Line Launch-lock release: 5 minutes
3. Thermal Stabilization: 24 hours*
4. Combiner & Collector Stand-alone Basic Health Tests: 2 hours
5. Combiner-Only Calibration/Alignment: 1 week (using internal source & stellar observations)
6. Interspacecraft Interferometer Communication Tests: 2 hours
7. Formation Checkout and Calibration: 2 weeks
8. Regular Observations: 6 months (1.5 hours per formation-observation, including slew; 4 per day)

*Note: desorption/outgassing associated with the composite structures will take somewhat longer to stabilize (~30 days) but this should be completed and/or well-characterized before regular observations begin.

The following sections provide brief descriptions of Combiner Calibration/Alignment, Formation Checkout and Calibration, and Regular Observations, which together provide a sampling of the nominal interferometer functions.

3.2 Combiner-Only Calibration/Alignment

The general philosophy for checkout, calibration, and alignment of the interferometer is an incremental, “walk before you run” approach, in which we boot-strap from step-to-step until optimal performance is achieved. Therefore, we begin by calibrating/aligning the interferometer using the Internal Test Source (ITS), which provides a direct comparison to pre-flight test results. This activity includes everything from removing pointing biases, misalignments, and beam-shear to assessing system throughput and white-light visibility. Once this process has been completed, it is repeated, this time using an actual star instead of the ITS. The sequence of events for Combiner-Only Calibration/Alignment is listed below:

1. Right stellar (ITS) acquisition (spiral search)
2. Right siderostat calibration
    a. update Siderostat-CCD gain matrices
3. Right stellar alignment
    a. align compressor/beam-combiner boresights
4. Right stellar shear adjustment
    a. remove internal shear
    b. throughput calibration
5. Right optical calibration
    a. Pointing & Fringe spot PSF/Plate-scale cal
    b. Background subtraction
    c. Spectral cal
6. Center right fringe spot
7. Repeat steps 1-6 for left arm of interferometer
8. Align Left & Right Fringe Spots
    a. Verify the two sides overlap
9. Left Metrology Alignment
10. System Identification ("plant" characterization)
    a. ADL system ID
    b. Siderostat system ID
11. Right & left stellar re-acquisition (with corrections in place)
12. ITS fringe acquisition & visibility calibration
13. Update Parameter Tables (non-volatile memory)
14. Repeat the above sequence with a real star (one with well-characterized properties)

3.3. Formation Checkout & Calibration

Once the Combiner-Only Calibration/Alignment is complete, the Collector (which has already completed its basic health tests, including communication checks with the combiner) is included and checkout/calibration of the formation-flying interferometer begins. It should be noted that up to this point, there has been very little interaction between the interferometer and spacecraft/formation-flying system other than basic services such as power, command and data handling, and combiner attitude-control. Now we begin the task of "handing-over" from the rather coarse control provided by the formation-flying system (limited by the 2 cm range, 5 arcmin bearing angle knowledge provided by the formation-flying sensors) to the precision control & knowledge provided by the interferometer (see Table 1).

1. Right Stellar Acquisition:
    a. This involves slewing the right siderostat to a predicted position (where any related biases have already been corrected by the previous calibration of the right combiner siderostat).
2. Initial Angular Metrology Acquisition:
    a. This is carried out at the minimum separation (range: 40 m, bearing: 12 deg), so as to maximize the angular diameter and intensity of the metrology beam at the collector (think of the metrology beam as a cylinder in the near-field regime, and a diverging cone in the far-field regime. The transition occurs at about 200 m). A search is performed by starting at the initial best estimate and then using the left combiner siderostat to steer the metrology beam in a square spiral pattern, until metrology photons are detected at the collector. At the completion of this step, the initial 5 arcmin bearing-angle knowledge provided by the formation-flying sensor is now reduced to 1 arcmin (bias-removal).
3. Initial Left Stellar Acquisition;
    a. This involves a spiral search with the collector siderostat to find the target star, again at the minimum separation to minimize any uncalibrated misalignment effects.
4. Metrology to Stellar Alignment (near-range)
    a. The metrology injection angle is adjusted (via the left beam-launcher actuator) to give zero shear.
5. Intermediate Left Stellar Acquisition

   a. Stellar acquisition is repeated in discrete steps while the collector is slowly maneuvered from a bearing angle of 12 deg to the maximum of 46 deg (the small steps intended to minimize siderostat motion during calibration).

6. Formation-Trimming (including Delay & Delay-Rate Estimation)
   a. Now at a range of 40 m and bearing of 46 deg, the formation is "trimmed" (rates nulled) using the interferometer and formation-flying sensors for delay and delay-rate information.
7. Initial Formation Fringe Acquisition & Measurement
   a. This is the first attempt to acquire fringes in formation-mode. Given the initial uncertainties, this first search may take more than the usual 100 mm of delay range. Fringe tracking and visibility measurements will allow a delay calibration for future searches.
8. Regular Formation Acquisition & intermediate fringe acquisition & measurement
   a. The formation is expanded from the shortest baseline (30 meters, range: 40 meters, bearing:46 deg) to the longest baseline (125 meters, range: 600 meters, bearing: 12 deg)….stopping along the way to acquire and track fringes, thus boot-strapping the delay calibration from point to point on the parabola.
9. Metrology to Stellar Alignment (repeat of step 4 at the far-range)
10. Regular Formation-Mode Observation Checkout
    a. Now that all calibrations are complete, a final set of observations are made at each parabola position (from far to near range) to confirm the calibrations before moving into the operational phase of the mission.

3.4 Regular Formation Observations

A typical formation-mode observation sequence consists of the following key activities:

1) Slew: Collector spacecraft maneuvers to the desired formation geometry (i.e., the proper separation/range and bearing angle corresponding to a given baseline) – this is the most time-consuming event (moving 100 meters takes 60 minutes). During the slew, the interferometer remains in SLEW mode, which maintains system thermal stability and keeps certain components such as the metrology laser and delay-line dither piezo-electric transducers in an "active standby" state. Towards the end of the slew, each spacecraft will make the necessary attitude adjustments to point the interferometer boresights near the target star. When the slew maneuver ends, the formation flying system will null out residuals (we assume this settle time will be one minute or so). At this point, the spacecraft reaction-wheels will be shut down to reduce jitter. Spacecraft attitude control during observations will be maintained with thrusters.

2)Acquisition & Observation: each Formation-Mode Acquisition and Observation should take about 30 minutes.

a. Right and Left Stellar Acquisition + Angular Metrology Acquisition: articulate the three siderostats per the predicts (spiral searching as necessary) until the star and Metrology laser spot are centered in the FOV and fringe spots are overlapped on the focal plane. This step is expected to take about 200 seconds.

b. Delay/Delay Rate Estimation & Trim Formation: since the Slew will have some residual range and bearing angle rates (formation flying system only has 2 cm and 1 mrad precision, respectively) some "fine tuning" is necessary before fringe acquisition can be attempted. This is because the aforementioned residuals will result in an uncertainty about where the fringe is located (in delay space) and the fringe will be moving at some unknown rate (which means even if acquired, it will be difficult to follow). Hence, the need to perform delay and delay rate estimation and, if necessary, request the formation flying system to trim the formation again – iterating until residuals are at an acceptable level. This process is still under study but for now we assume it could take 1000 seconds to complete (if there's some iteration).

c. Fringe Acquisition & Tracking: The fringe tracker uses delay and delay-rate solutions from the Interferometer Estimator to provide a starting point for Coarse Fringe Acquisition– the ADL puts the delay in the "ball-park" (within a ± 20 mm window). The ADL then begins scanning at rates of 100 µm/s using the camera white-light fringe spot for feedback with a visibility variance algorithm. Once delay and delay-rate knowledge have been refined to the ±10 µm and 3 µm/s levels, respectively, the Fringe Tracker transitions to Fine Fringe Acquisition. At this point, the dither PZT modulation is activated to provide a pre-programmed "stair-case" pathlength modulation across the estimated fringe position. The spectrometer data is used by a "4 bin" algorithm to estimate fringe phase and improves the knowledge of fringe position via group-delay estimation[12]. At this point, fringe measurement begins. The single white-light and 4 dispersed fringe pixel data will be buffered at 500 Hz for downlink (along with error estimates from the other control loops and various engineering data). The white-light fringe data is co-phased with the dispersed fringe data a posteriori to improve overall fringe SNR.

The fringe measurement stage of an observation typically lasts about 200 seconds. We expect to momentarily lose fine fringe lock during thruster firings (which are constrained to 3 second windows every 30 seconds) but the Fringe Tracker will maintain 1.3 µm/s delay rate knowledge and automatically restart fine fringe acquisition over an ADL search range of ± 10 µm following thruster firing (expandable to ± 30 µm if fringe lock isn't quickly re-established).

When complete, this process repeats with the formation slewing to another baseline configuration. Our current plan is to complete all baseline configuration observations on a single target before moving on to the next although there are advantages to changing pointing and sampling a number of stars at each baseline. The expected rate of formation observations is about 4 per day.

4. CONCLUSIONS

The StarLight formation flying stellar interferometer, as either a flight project or ground technology program, will demonstrate new technologies necessary for TPF and other future astrophysics missions. By carefully characterizing the system performance by obtaining fringe visibility measurements on a variety of targets over a range of baselines, we will validate our components, algorithms, and processes. In this paper, we summarized the overall interferometer system architecture and some key operational concepts consistent with the StarLight Project Design Capture of March 2002.

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REFERENCES

1. C.A. Beichman, N.J. Woolf, and C.A. Lindensmith, editors, "The Terrestrial Planet Finder (TPF) – A NASA Origins Program to Search for Habitable Planets", *JPL Publication 99-3,* May 1999.
2. O.P. Lay, G.H. Blackwood, "Formation Telescopes and the StarLight Mission", *SPIE Conference 4852 (these proceedings),* 2002.
3. G. Blackwood, O.Lay, B. Deininger, M. Gudim, A. Ahmed, R. Duren, C. Noecker, B. Barden, "StarLight Mission: a formation-flying stellar interferometer", *SPIE Conference 4852 (these proceedings),* 2002.
4. P.W. Gorham, W.M. Folkner, and G.H. Blackwood, "Enabling Concepts for a Dual Spacecraft Formation-Flying Optical Interferometer for NASA's ST3 Mission", *Dana Point Conference on Optical Interferometry*, 1999.
5. R.M. Duren, O.P. Lay, "The StarLight Formation-Flying Interferometer System Architecture", *IEEE Aerospace Conference, 6-0505*, March 2002.
6. S.R. Martin, R.M.Morgan, S.M.Gunter, R.D. Bartos, *SPIE Conference 4852 (these proceedings),* 2002
7. O.P. Lay, G. H. Blackwood, S. Dubovitsky, P.W. Gorham, R. P. Linfield "Design of the ST3 Formation Flying Interferometer", *Dana Point Conference on Optical Interferometry*, 1999
8. S.Dubovitsky, O.Lay, and A.Abramovici, "The StarLight Metrology Subsystem", *IEEE Aerospace Conference, 6-0507,* March 2002.
9. R. L. Grogan, G. H. Blackwood, and R. J. Calvet, "Optical Delay Line Nanometer Level Pathlength Control Law Design For Space-Based Interferometry," *SPIE Astronomical Telescopes*, April 1998.
10. R. J. Calvet, B. Joffe, D. Moore, R. L. Grogan, and G. H. Blackwood, "Enabling Design Concepts for a Flight-Qualifiable Optical Delay Line," *SPIE Astronomical Telescopes and Instrumentation*, April 1998.
11. R. Duren, etal, "StarLight Interferometer System Operations Plan", *JPL Document*, February 2002.
12. M. M. Colavita, "Fringe Visibility Estimators for the Palomar Testbed Interferometer", *PASP, 111, 111-117,* 1999.